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TITANIUM IN AEROSPACE STRUCTURES

A CASE STUDY OF THE INTERACTION BETWEEN
MATERIAL DEVELOPMENT AND APPLICATION

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TITANIUM IN AEROSPACE STRUCTURES

A CASE STUDY OF THE INTERACTION BETWEEN MATERIAL DEVELOPMENT AND APPLICATION

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ABSTRACT:

Material development and structural application of titanium are reviewed for the purpose of making the accumulated experience available for the development of future advanced materials. Two types of interaction are considered: materials development and structural application as well as materials selection and structural application. The process of selecting a material for structural application is investigated from the viewpoint of engineering design. It is shown that titanium provides a valuable case study because it is the first material developed on a large scale for the complex conditions of high-performance aircraft.

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1. INTRODUCTION

Development of titanium began after World War II. The infant material showed outstanding specific strength, particularly at elevated temperatures, and the promise of wide application as a structural material for advanced aircraft justified a large-scale development effort.

Two decades of intense interest in titanium have passed since then. Many difficulties arose as this new material compounded the existing complexities in the field of high-performance aircraft. Results were achieved gradually, and, with the progress of extensive research and development, titanium has now taken its proper place among other structural materials.

A multitude of information has been published on many aspects of this work. Most of it is concerned with the detail peculiarities of titanium technology. Not much consideration has been given to an overall viewpoint. It seems that many urgent problems had to be solved first, and some of the broader aspects and implications were relegated to the background.

It is the purpose of this study to investigate one of these broader aspects: the relationship between the development of titanium and its application to aerospace structures.

This includes appreciation of the difficulties encountered during the development process. It also includes general considerations which lead to the selection of a material and to the choice of the corresponding structure. Finally, last but not least, it takes into account that titanium development pioneered the complex process leading to the application of a new material in aerospace structures under present conditions. Much can be learned from this experience with titanium.

This study is based on three fundamental considerations which appear to be particularly pertinent:

First, in order to understand the technological situation, a historical review furnishes the necessary background and leads to the present state of the art. A brief outline of titanium development from a non-technical viewpoint is given in section 2; the major technological aspects of this development are shown in section 3; examples of titanium application to aerospace structures are listed in section 4.

Second, in order to understand the competitive situation, the decision process concerning the selection of material and structure is considered. Competition between various materials, such as titanium vs. aluminum, is affected by many factors. Design considerations regarding material, structure, weight and cost are shown in section 5; the relationship between material and structural application is summarized in section 6.

Third, in order to understand the future situation, some conclusions may be drawn from the foregoing technological and competitive considerations. This is done in section 7.

The scope of the investigation is confined within certain bounds. For this reason, after a general review of aerospace structures, design considerations are limited to aircraft only rather than aerospace vehicles in general. Another limitation is imposed by considering turbomachinery, which accounts for a large share of titanium production, to be a separate subject which is not included as part of structures.

Due consideration for the gradual process of developing titanium should not be interpreted as a mere historical exercise. It rather provides the proper perspective for understanding the material and

its application. Such an overall viewpoint is useful not only in applying titanium but also in realizing the difficulties which must be anticipated in the development of any new material.

This study attempts to identify those aspects of titanium development which are significant in terms of present and future problems of material development, material selection and structural design. In surveying these subjects, reference is made to an ample literature which contains full detail information. Reiteration of such details is generally avoided in order to limit this investigation to a concise outline emphasizing the interrelation between various fields. There is a growing awareness of the pervasive influence of this interrelation. Complexities and implications of the subject are impressive and a case study for titanium can help to clarify the general approach to this problem of interaction between material and structure.

2. GENERAL OUTLINE OF TITANIUM DEVELOPMENT IN THE UNITED STATES

2.1. Beginning of Titanium Production

Titanium was discovered in 1790, but it remained dormant for over a century. The reason for this can be found in the affinity of molten titanium for gases and other materials which made ore reduction very difficult.

The obstacles were overcome by development of the Kroll Process which was adopted by the U. S. Bureau of Mines for experimental production during World War II. Steady progress with experimental methods resulted in the beginning of a titanium industry during the late 1940s (39, 65).

Production of titanium consists of three steps (39) which are combined into an integrated process by some producers while others have facilities for only one or two of them:

First, reducing ore by a magnesium or sodium process into titanium sponge;

Second, remelting and alloying the raw material into titanium ingots;

Third, mill processing and heat treating the raw ingot to various mill products.

Titanium is the ninth most frequent element in the crust of the earth. It is found in sand, clay and rock. Its availability is virtually unlimited, with ample domestic resources even if much of the ore is presently imported from Canada, Australia and other countries.

For the purpose of giving a brief outline of titanium developments, without any technological details, it may be convenient to consider separately the first and second decades of its production (Ref. 85, 103, 48).

2.2. Period of 1948 - 1957

The great potential of titanium was clearly recognized from the beginning. The economic implications for the development of this new material, however, could not be anticipated. There was a clear discrepancy between the future value of titanium as a strategic material and the economic risk of a new technological development.

This gap was bridged with the Defense Production Act of 1950. It gave the Federal Government authority and funds to support an industrial expansion for titanium sponge production and melting and fabricating facilities. Subsidies were given in various forms: plant construction loans, accelerated tax amortization, purchase commitments, research and development grants, etc.

Many companies became interested in this new industry but only a few proceeded to the point of commercial production. Much organizing and reorganizing took place. A great number of administrative agencies, advisory groups and assistance programs were involved, and also congressional committees took an active interest (85, 103).

This period was characterized by much hope and optimism. It saw the birth and rapid expansion of the titanium industry, which provided a new metal in sufficient quantities for large-scale production of high-performance aircraft. It also produced many a

disappointment because technical difficulties were greater than had been anticipated. It finally ended with a very severe blow in 1957: most government subsidies for titanium production were terminated abruptly due to over-capacity of the fast-growing titanium industry.

The situation was described aptly by Business Week of Nov. 16, 1957: "Producers of the wonder metal are wondering where the wonder went." The serious consequences for productive capacity are indicated in Figure 1.

Only two out of six producers of titanium sponge survived in 1964. The reasons may be found mostly in two basic circumstances: overestimating the need for titanium in the near future and underestimating the difficulties in the development of a new material. Severe cutbacks in aircraft production and increasing emphasis on missile development contributed to uncertainties for any forecasts. In addition, the seriousness of the situation was accentuated by a temporary reduction in use of titanium for jet engines which took place at the same time and had a very detrimental influence.

*   *   *

Summarizing the first decade of titanium production:

The primary emphasis was on production and this was accomplished. It was a somewhat hectic period of rapid expansion and it provided important lessons regarding the development of a new industry -- but this is beyond the scope of the present study.

Much basic information was developed in the fields of metallurgy and production of titanium, but great difficulties remained in the field of titanium application. Lack of uniformity in material production, warping, spring back, cracking, need for developing new methods for machining and welding and many other problems plagued the industry.

2.3 Period of 1958 - 1967

The second decade started with all the problems which had not been solved in the first decade. In spite of the serious situation for titanium production and severe cutbacks in subsidies, research and development continued in a systematic process. The foundation for this had been laid in the mid-1950s.

First of all, the Battelle Memorial Institute began to act as a central agency for titanium research and development, an activity which was grouped subsequently in its Defense Metals Information Center. It has been providing important advisory services to industry as well as conducting research and summarizing and disseminating available information. Its publications have been used as basic reference.

Second, in 1956, the Titanium Alloy Sheet Rolling Program was organized by the Department of Defense for the purpose of solving some basic problems of production and engineering. It did outstanding work in advancing titanium technology, and published its final report in 1962 (71). More will be said about this work in section 3.2.

Third, in 1961, the Special Committee on Materials Research for Supersonic Transports was established by NASA. This coincided with the time when ideas about a supersonic transport began to crystallize. The attention of this committee was concentrated on sheet material of titanium as well as stainless steel and super-alloys (79, 80). Much valuable work was done in systematic screening of materials and recommending additional research. More will be said about this work in section 3.3.

These three agencies had a decisive influence on providing a clear and purposeful guidance for the development of titanium. It was mostly due to their methodic and thorough work that the second decade of titanium production became distinctly different from the first decade.

A good summary of the status of titanium development in the mid-1960s can be obtained from two publications: Reference 21 is a basic reference for the properties of titanium and titanium alloys and contains some 600 selected references for various categories of interest; Reference 24 gives various aspects of the state of the art in titanium metallurgy, fabrication and design.

The accelerated pace of titanium production after 1965 is shown in Figure 1. It can be seen that in recent years sponge consumption exceeded sponge capacity. This made it necessary to import some titanium sponge, mostly from Japan and the United Kingdom.

The prices for titanium sponge and mill products have declined asymptotically to values of $1.32 and $5.95[1] per pound, respectively (Figure 2). Titanium is fundamentally more expensive than steel or aluminum due to the more complex process of ore reduction. It is doubtful whether this process can be basically improved. If attempts in this direction should be successful, the market for titanium could be expected to expand far beyond the aerospace industry.

In 1967 approximately 50% of titanium production went into jet engines while aircraft and spacecraft structures took close to 25% each (69). A small percentage went into non-aerospace applications, mostly in the chemical industry due to the good corrosion resistance of titanium. Further developments will depend very strongly on the supersonic transport program.(69)

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[1]The $5.95 figure is the Titanium Metals Corporation of America's composite price for mill products which is the average of the base prices plus extras for four types of mill products:

(1)	Ti-75A	.30 x 36 x 96 in. sheet
(2)	Ti-75A	.016 x 20 in. coil strip
(3)	Ti-5AL-2.5Sn	1 in. rod
(4)	Ti-6AL-4V	8 1/2 in. dia. billet

* * *

Summarizing the second decade of titanium production:

It was a period of systematic technological improvements. Most of the technical difficulties of the first decade were overcome by increasing experience. There are, however, still a good number of older and newer problems which call for a continuing research effort (46).

Titanium had disappeared somewhat from the limelight of a glamorized position after its first decade. It came back to public attention in 1964 when the existence of a titanium aircraft was announced (105). This indicated that the development period was coming to an end and titanium was taking its proper position with other materials.

3. TECHNICAL ASPECTS OF TITANIUM DEVELOPMENT

In the preceding section a brief overview of titanium development was given. It was indicated how a technological development may be influenced by many non-technical factors -- frequently beyond the jurisdiction of engineers and scientists.

In the present section technological aspects of titanium development are considered. Only brief outlines are given for most of the major steps; reference should be made to the literature listed in the bibliography for further details. Considerations of stress corrosion and crack propagation, however, are shown in greater detail because they present an outstanding example for unforeseen difficulties which can arise in spite of carefully planned research and development.

3.1. Early Problems

Titanium had its share of development problems in the early stages of its introduction to the aircraft industry. Basically, the problems were related to:

(1) the reactivity of titanium, which complicated ore reduction, melting, mill processing, machining and forming;

(2) the high yield strength and low modulus of elasticity, which made forming and machining difficult and led to problems in elastic recovery (springback) and warpage in the presence of residual stresses.

These difficulties in production and fabrication were overcome slowly as great efforts were extended. By the late 1950s, new equipment and procedures had been developed for titanium production processes, making titanium comparable to other aircraft structural materials from a manufacturing standpoint.

Detail problems encountered in the early period of development were the following (23, 25, 48):

(1) sponge quality -- initial production had hardness of 240 Brinell which caused difficulty in production of ductile parts;

(2) non-homogeneity in single-melted ingots -- solved by developing a double arc-melting process using consumable electrodes in a vacuum atmosphere;

(3) hydrogen embrittlement -- also solved by the vacuum melting process;

(4) poor stress corrosion resistance in hot salt environment above 600°F -- minimized by limiting exposure to below 600°F and maintaining clean surface of parts during stress relieving;

(5) problems in fabrication and forming -- solved by perfecting new procedures;

(6) reliability of mill products -- solved by developing new techniques and milling equipment designed for titanium instead of steel.

3.2. Titanium Alloy Sheet Rolling Program

This program was initiated by the Department of Defense and was carried out under the guidance of the Materials Advisory Board

of the National Research Council from 1956 to 1961 (71). The goal was to develop large flat sheet of good formability, high strength, satisfactory fabricating characteristics, uniformity and reproducibility.

The program was divided into three phases:

Phase I - Manufacturing Development

to develop optimum production techniques and fabrication standards applicable to the entire titanium industry;

Phase II - Design Data Accumulation

to compile design data for selected alloys, based on uniform testing procedures;

Phase III - Material Evaluation

to evaluate fabricability, reliability and serviceability of selected alloys and to familiarize the aircraft industry with the new materials.

Government, research agencies, titanium producers and airframe manufacturers were working together on many panels and subpanels, conducting a large-scale effort. Much confidence was gained as this program resulted in an outstanding success. The magnitude of the task may be appreciated if one realizes that at the inception of the program titanium still was a rather new material; that it had been used only on a very limited scale, never in form of high-strength, heat-treated sheets; that no tradition existed for manufacture, processing, inspection, design or service experience; that a multiplicity of variables had to be taken into account; and that no precedent for such a vast effort existed, at least under peace time conditions.

Phases I and II resulted in uniform titanium products meeting clearly defined design requirements.

Phase III provided a valuable and necessary opportunity for the aircraft industry to develop the experience and the level of confidence which are required for successful incorporation of titanium alloys into aircraft structures.

3.3. Materials Research for Supersonic Transports

In 1960, much attention began to focus on the possibility of a commercial supersonic transport, and NASA made the initial effort to correlate the various parameters governing the design and operation of an SST. It became evident that no individual company possessed the resources and technology to develop the SST. Therefore, DOD (Air Force), FAA and NASA launched a combined effort to formulate a long-range program to develop a suitable SST.

In 1961, NASA established the Special Committee on Materials Research for Supersonic Transports. Although unknown problem areas were anticipated in all SST materials, the committee initially limited its investigation to sheet materials for the wing and fuselage. In 1963, the committee made an interim report (80) in which the number of alloys under consideration was reduced from 27 to the eight most promising. The alloys recommended for further evaluation were: AM350, AM355 and PH 14-Mo steels; 8Al-1Mo-1V and 6Al-4V titanium alloys; and René 41, Waspaloy and Inconel 718 superalloys. In addition, the committee recommended further investigation into stress corrosion of stainless steels and titanium alloys in a hot-salt environment.

In 1963, feasibility studies of an SST and related technological projects were conducted. Four design concepts, originated by NASA, were studied by two aircraft companies, Boeing and Lockheed. The results of these studies (72) were presented to the NASA Conference on Supersonic Transport Feasibility Studies and Supporting Research.

Both companies chose basically a skin-stringer type of construction using Ti-8Al-1Mo-1V duplex annealed alloy for all Mach 3 studies (66). Each concluded that two of the four designs were worthy of further study. Finally, both discovered that the gross weight of an aluminum Mach 2.2 aircraft would be 21-30 per cent heavier than a Mach 3.0 titanium aircraft.

Some significant conclusions of the review of the NASA Committee on Research on Materials Applicable to Supersonic Transport (36) presented at the conference were:

(1) Hot-salt stress corrosion was almost nil in Ti-4Al-3Mo-IV, moderate in Ti-6Al-4V and severe in Ti-8Al-1Mo-1V.

(2) Of the contending materials, Ti-8Al-1Mo-1V alloy appeared to be superior, except when subjected to hot-salt stress corrosion.

3.4. Stress Corrosion and Crack Propagation

In titanium's early period of development, its outstanding corrosion resistance characteristics in numerous environmental conditions favorably supplemented its other properties. Subsequently, certain environmental conditions were found to produce a profound effect on titanium alloys.

Three prominent corrosion-related problems have a significant position in the history of titanium development as related to the aerospace industry: hot-salt stress corrosion, stress corrosion in nitrogen tetroxide and increased crack propagation of pre-notched specimens under stress in an aqueous, room-temperature environment.

Controversy as to the mechanism of environmental stress corrosion and increased crack propagation currently exists and much investigation is being conducted to pinpoint the causes and to investigate suitable remedies. Reference 53 summarizes the controversy and mentions current remedies to reduce environmental stress corrosion. In addition, the reader is referred to References 16, 20, 44 and 45 for a more complete coverage of corrosion of titanium and its alloys.

3.4.1. Hot-salt Stress Corrosion

Originally, titanium was considered to be susceptible to stress corrosion only when subjected to anhydrous red fuming nitric acid (48).

In 1955, surface cracking was observed on Ti-6Al-4V alloy specimens which were subjected to creep testing at 700°F. In some cases this phenomenon was traced to salty fingerprints. Further laboratory tests of salt coated specimens at elevated temperatures confirmed that hot salt caused stress corrosion of titanium alloys.

In 1963, Ti-8Al-1Mo-1V alloy was chosen as the candidate material for an SST feasibility study with the recommendation that an investigation of the hot-salt stress corrosion problem be conducted prior to final material selection (36).

In December 1963, Braski and Heimerl (9) reported on the susceptibility of four titanium alloy sheet materials to hot-salt stress corrosion at 500°F. Ti-4Al-3Mo-1V alloy proved to be the most resistant to hot-salt stress corrosion, Ti-6Al-4V and Ti-13V-11Cr-3Al alloys showed intermediate resistance and Ti-8Al-1Mo-1V alloy was the most susceptible.

The basic parameters of hot-salt stress corrosion were determined to be temperature, stress level and length of exposure. Figure 3 is a typical presentation of hot-salt stress corrosion, indicating the existence of a threshold boundary.

In a 1964 investigation of several titanium alloys, Lockheed (98) reported that heat treatment had a definite effect on stress corrosion behavior. Subsequent studies revealed that thickness also affected hot-salt corrosion resistance and verified the fact that hot-salt corrosion was considerably reduced during cyclic exposure, compared to long-time exposure (62, 97, 99).

In 1965, Carter (11) reported that tests indicated that an SST operating at Mach 2.7 would be adequately below the stress, temperature and time threshold at which damaging hot-salt stress corrosion may occur. Also mentioned in the article was the discrepancy between cyclic and long-time exposure, which led to the postulation that hot-salt stress corrosion may only be a laboratory phenomenon. This postulation was supported by Bomberger (7), who reported that the hot-salt corrosion phenomenon had only been reported in laboratory experiments.

In a paper presented in 1967, Pride, et al. (78), summarized the effects of long-time exposure (10,000 hrs.) of various SST sheet materials to a hot-salt environment. It was concluded that hot-salt stress corrosion cracking of titanium alloys would not be a problem for a Mach 2.7 transport airframe with operating stresses below 25 ksi and operating temperatures below 450°F.

An example of an attempt to better simulate actual SST environmental conditions is an investigation conducted by Weber and Davis (102). Specimens of Ti-6Al-4V and Ti-8Al-1Mo-1V alloys were subjected to Mach 2.5 airflow in a wind tunnel at a simulated altitude of 70,000 feet and a temperature of 600°F and 700°F for periods up to 50 hours. Their results indicated that hot-salt stress corrosion effects in a supersonic airstream were considerably less than those produced in laboratory oven tests. Correlation between salt removal due to the high velocity airstream and cracking damage was indicated.

Tests are continuing to improve the resistance of titanium alloys to hot-salt stress corrosion (8, 81, 87, 88, 89, 90, 91). Stein, et al. (87), investigated effectiveness of various coatings and surface treatments on Ti-8Al-1Mo-1V alloy sheet at 600°F. The results were the following:

(1) Nickel and aluminum coating were effective in preventing hot-salt stress corrosion for at least 10,000 hours;

(2) Polyimide coating peeled off the surface after 500 hours of exposure;

(3) Glass-bead peening appeared to be effective in preventing or alleviating hot-salt stress corrosion for at least 10,000 hours;

(4) Vibratory treatment proved to be effective for at least 15,000 hours.

3.4.2. Increased Crack Propagation

In 1965, the phenomenon of increased crack propagation of a titanium alloy under stress in a room temperature, salt-water environment was discovered. This discovery stimulated the companies and agencies involved with SST development to re-evaluate their material selections (62).

Boeing conducted extensive tests to establish alternate alloys and heat treatments that would improve fracture toughness and resistance to environmental crack growth. It was determined that properly heat-treated alloys, Ti-6Al-4V and Ti-4Al-3Mo-1V, provided adequate strength, toughness and resistance to environmental crack growth for SST applications (5, 15, 43).

Lockheed commenced a thorough investigation into improvement of the stress corrosion and increased crack propagation characteristics of Ti-8Al-1Mo-1V and other titanium alloys for SST application (62, 63, 97, 99). Ti-8Al-1Mo-1V duplex annealed alloy had been determined to be the optimum material for thin-skinned applications in the Lockheed design proposal due to its better fracture toughness, creep resistance and stiffness characteristics.

In regard to increased crack propagation, Lockheed concluded the following:

(1) Increased crack propagation of titanium alloys is a function of heat treatment and thickness of the material.

(2) The alloys selected were comparable to their counterparts in subsonic transports with regard to increased crack propagation.

(3) The increased crack propagation problem may be a laboratory phenomenon. Wide sheet specimens were not susceptible to increased crack propagation; whereas, the commonly used narrow specimens were.

As a result of the studies, Lockheed modified their proposed utilization of titanium alloys. Ti-8Al-1Mo-1V duplex annealed alloy, the original choice for SST application, showed increased susceptibility to salt-water crack propagation in gages greater than 0.03 in. A newly developed heat treatment, designated special mill process (SMP), was determined to provide protection in thicker gages. Therefore, for its final material selection proposal, Lockheed selected a mixture of alloys (mostly Ti-8Al-1Mo-1V and Ti-6Al-4V) and heat treatments which satisfied gage requirements and provided maximum resistance to hot-salt stress corrosion and increased crack propagation.

The role of cyclic loading in crack propagation characteristics of titanium alloys was investigated thoroughly during the XB-70 development. Reinsch (83) reported that tests indicated adequate resistance to crack propagation under cyclic loads similar to those expected for the XB-70.

3.4.3. Stress Corrosion in N_2O_4

As numerous tests were being conducted concerning titanium alloy application to the SST, problems of environmental stress corrosion and increased crack propagation of titanium alloys appeared in space applications (49, 61, 73). During tests it was discovered that many liquid propellant tanks constructed of Ti-6Al-4V alloy had experienced catastrophic failures.

In 1967, the Defense Metals Information Center sponsored a seminar on "Accelerated Crack Propagation of Titanium by Methanol, Halogenated Hydrocarbons, and Other Solutions" (20). All aspects of environmental effects on titanium alloys were discussed in great detail. At that meeting it was reported that original room temperature stress corrosion tests of Ti-6Al-4V alloy for use as the material for nitrogen tetroxide (N_2O_4) oxidizer tanks had revealed no problems. Subsequently, tests of tanks containing N_2O_4 and placed under stress produced failure in as little as 30 hours under stress levels of 30 to 135 ksi and temperatures of 85°F and 165°F. In addition, tests of tanks containing methanol, a substitute test fluid for N_2O_4, produced failure under stressed conditions in as little as three hours (73).

NASA conducted a recent study to determine effects of time, temperature and stress on the stress corrosion of Ti-6Al-4V alloy in N_2O_4 and to develop possible methods for alleviating the corrosion (61). Temperature ranged from 65°F to 165°F and stress level from 25 to 100 ksi. The following results were obtained:

(1) At 165°F, stress corrosion cracking was severe and resulted in failure within four hours of exposure. The damage diminished rapidly with decreasing temperature.

(2) At 75°F, no stress corrosion damage was observed for exposure up to 500 hours.

(3) The time for crack initiation was not dependent on stress level.

(4) Metallic and organic coatings investigated were found to be unsatisfactory for protecting Ti-6Al-4V alloy against stress corrosion, but surface-induced residual compressive stresses produced by glass-bead peening were found to be effective.

(5) Addition of a small amount of nitric oxide (0.78 per cent by mass) to the N_2O_4 resulted in no stress corrosion in small test specimens.

3.5. Machining, Forming and Joining

Initially, titanium was considered to be very difficult to machine, form and join compared to other materials. The difficulties encountered were mainly due to the quality of original mill products, the reliance on steel manufacturing equipment and techniques, the reactivity of titanium and the lack of experience with the new material.

Steady improvements were made in small steps and the Titanium Alloy Sheet Rolling Program contributed greatly to the advancement of heat treating, forming and joining of titanium alloys. Progress in manufacturing processes and techniques has advanced to the point where titanium now competes with other structural materials from a manufacturing and fabrication viewpoint. Cost of titanium fabrication is

generally higher than for aluminum, however. Several aspects of materials processing are investigated in References 33, 38, 55, 68, 70, 83, 86 and 96.

3.5.1. Machining

Early problems in the machining of titanium alloys originated from high cutting temperatures, adverse tool wear due to the chemical reactivity of titanium with the tool face and distortion due to titanium's relatively low modulus of elasticity.

With the progressive refinement of tool materials, tool geometry, and fabricating procedures, the machining of titanium alloys has now become routine, and it is reported that more consistent results can be obtained with titanium alloys than with some grades of steel (58, 74). However, high-quality machine tools and cutting tools as well as strict adherence to recommended machining practices are required.

Of the non-mechanical metal removing methods, chemical milling and electrochemical machining are widely used; electric-discharge machining is still in a somewhat experimental stage.

3.5.2. Forming

Forming of titanium requires more control and care than with other metals due to its reactivity and springback characteristics. During the early stages of titanium history, variable springback was encountered.

Two basic forming techniques for titanium alloys were adopted by the titanium industry during the DOD Sheet Rolling Program: hot forming and cold forming-hot sizing. Hot sizing consists of the controlled application of pressure, temperature and time to cold formed parts. This operation serves to correct the springback and also relieves the residual stresses introduced by forming operations.

Progress in forming techniques of titanium alloys has continued, and today titanium alloys can be transformed into useful shapes almost as readily as many of the aluminum alloys and nickel-bearing steels.

3.5.3. Joining

Much time was required to develop joining techniques. Titanium alloys may be joined by mechanical fastening, brazing, adhesive bonding, fusion welding, resistance welding and metallurgical bonding.

Mechanical fastening methods are necessary for non-permanent joints but they are also used for other applications. Considerable experience has been accumulated regarding hole preparation, selection of bolt or rivit material and evaluation of joint properties.

Adhesive bonding techniques which were developed for aluminum and steel are generally applicable to titanium. However, only limited experience is available for adhesive-bonding technology on titanium (52).

Brazing finds its widest application in fabricating honeycomb sandwich panels. Great care is required to prevent contamination of titanium by leakage of air into the brazing atmosphere.

Fusion welding in its various forms, including electron-beam welding, has been developed into a well-established technology. Inert-gas shielding is used extensively to prevent weld contamination (70, 96).

Resistance welding is used widely in form of spot welding or seam welding.

Metallurgical bonding is a solid-state bonding process. Either diffusion or deformation play a major role as the joint is formed without melting of the component parts.

A particularly interesting application of deformation bonding is the roll-welding process developed at the Battelle Memorial Institute under the sponsorship of Douglas Aircraft Company (42, 48). It is used for fabricating unidirectional sandwich panels with a corrugated core. Face sheets and corrugated core are passed through a rolling mill which applies the desired pressure and produces the proper deformation for bonding. Mild-steel inserts are needed to support the truss core during the process and are removed afterwards by leaching. The resulting joint is a continuous solid-state bond which has the same properties as the base metal. The panels can be contour-formed immediately after bonding.

In 1967, North American completed an investigation of the application of roll-welding techniques to produce integrated "T"-stringer-skin panels for possible use in the Saturn I-C rocket (50). Integrated stringer-skin panels manufactured by roll-welding show great promise; however, problems of steel filler bar removal and thermal distortion continue to deter economic utilization of this method.

3.6. Titanium Alloys and Their Physical and Mechanical Properties

Establishment of physical and mechanical properties forms the foundation for the structural application of titanium. These values are listed in Reference 21 and, in a somewhat condensed form, in Reference 26. Additional information can be found on new titanium alloys in References 14, 17, 51, 77 and 106.

For the purpose of this study, no attempt is made to discuss detail values. Only some typical examples are given in section 5 to illustrate those aspects of material characteristics which influence the selection for structural applications. Special attention, however, should be called to some basic considerations:

(1) Mechanical properties are not easily established in a satisfactory way for aerospace structures. Temperature range, environmental conditions, exposure time, load spectra, etc., impose a very large number of parameters. This makes it imperative to extend material testing far beyond the scope which had been customary previously. This testing is expensive not only in terms of money but also in terms of time.

(2) In addition to the parameters mentioned under (1), the sequence of loading or of environmental conditions can be of influence. Also, as seen in section 3.4, the possibility exists that test conditions are not representative of actual conditions.

(3) Conventional materials, like steel or aluminum, were developed slowly. Each new alloy or heat-treatment or processing method was based on preceding experience. Titanium development, however, took place at a different pace. In many cases, the material had to be prominently applied without the benefit of thoroughly accumulated experience. This results in high demands on experimental and theoretical evidence as well as engineering judgment.

(4) Experience on aerospace structures has shown that new and additional material criteria must be used. The concept of fracture toughness has been developed in recent years as an important criterion for the ability of a material to contain damage. The concept of crack propagation results in a critical crack length beyond which a crack propagates rapidly at a given stress. Tests for fracture toughness criteria have not been standardized yet and data are used at present for qualitative information only.

(5) The importance of many of the physical properties depends on the application of the material. For thermal stresses, for instance, the product $E\alpha$ (modulus of elasticity x coefficient of thermal expansion) is an important parameter.

4. APPLICATION OF TITANIUM TO AEROSPACE STRUCTURES

4.1. General Survey

Application of titanium to aerospace structures increased steadily as manufacturing processes improved. Table I gives a sampling of aircraft and space capsules and indicates the use of titanium and titanium alloys in per cent of structural weight.

In the beginning, titanium was used primarily for firewalls and other simple applications in the high-temperature regions of nacelles. This amounted to hardly one percent of the airframe weight.

During the mid-1950s, sheet-stringer construction, forged parts and titanium-aluminum sandwich panels were introduced into airframe construction, increasing the total amount of titanium in fighter and attack aircraft up to about 7% of the airframe weight. Experimental high-speed aircraft like the X-15 and XB-70 utilized a higher percentage of titanium.

Missile and space structures soon captured an increasing percentage of titanium application. Mercury and Gemini space capsules used titanium as the principal structural material. Atlas pressure vessels and Minuteman rocket cases are other examples for titanium application in space.

By the mid-1960s, titanium technology had progressed sufficiently to make its large-scale application to airframes feasible. Titanium is used primarily in regions of elevated temperature, yet it becomes increasingly competitive for certain applications at room temperature.

Some typical applications of titanium in aerospace structures are listed in greater detail on the following pages.

4.2. Typical Examples

4.2.1. F-100, F-102, F8U

Spot and seam welding techniques were applied extensively to the titanium and titanium alloys used in the tail sections of the North American F-100, Convair F-102 and Chance Vought F8U (23).

4.2.2. A3J

Various titanium applications in the North American A3J are representative of the state of the art of titanium development during the 1953-1957 period (25).

Inlet ramps were constructed of titanium-aluminum sandwich consisting of Ti-8Mn plates bonded to aluminum honeycomb core. Titanium was chosen for use in ramp construction primarily for its corrosion resistance. In addition, the production model ramp weighed considerably less than an aluminum version.

Extrusions of Ti-5Al-2.5Sn were used with great success. Riveted sheet-stringer engine access doors of considerable size were utilized in the high temperature area surrounding the engines.

Of particular interest, the largest titanium alloy forging to that date was a rib of the horizontal stabilizer. The titanium alloy (Ti-6Al-4V) rib saved 30 lbs. over an equivalent steel forging.

4.2.3. XB-70

In 1955, the design of the Mach 3 XB-70 intercontinental bomber was formulated.

Reference 1 describes the structural design and material utilization of the XB-70 and summarizes the results of flight test experience as applied to material performance.

The airframe contains a variety of high strength steels, titanium alloys and heat resistant alloys. The majority of the airframe is constructed from Ph-15-7Mo steel. Titanium alloys account for nine per cent (12,000 lbs) of the structural weight.

Peak operating temperatures are 475°F for the majority of the airframe, 630°F for the leading edges and inlet ducts and as high as 1000°F in the engine compartment.

The delta wing is of multi-spar construction with brazed steel honeycomb sandwich surface panels. Honeycomb sandwich was chosen due to the requirement to insulate the fuel in the integral fuel tanks (83).

The forward section, which houses the crew and electronic equipment, is constructed primarily of titanium alloys. The crew compartment has a Ti-4Al-3Mo-1V alloy substructure covered by Ti-6Al-4V alloy skin. The equipment compartment is of skin-stringer construction with titanium alloy skin and frames and steel longerons.

Other applications of titanium alloys are in the Canard surface, the veritcal stabilizers and in the aft fuselage section.

An evaluation of materials during the flight testing program reported that the titanium alloys performed quite satisfactorily.

4.2.4. X-15

The X-15, whose structure has 17.5 per cent titanium by weight (115), was also designed during the late 50's. Its design represents an important application of weight saving consideration in conjunction with a high temperature environment. Since the X-15 was designed for flight at Mach 5, Inconel X was selected as the primary material for the hot airframe structure. In the forward fuselage, titanium alloys are used for the frame which supports the Inconel X outer skin and aluminum inner skin. The aft fuselage consists of a titanium substructure supporting an Inconel X primary structure. Titanium is also used in the frames and ribs of the wings.

4.2.5. Mercury

The basic structure of the Mercury space capsule was of titanium construction (48). A two layered, truncated cone of unalloyed titanium was spot welded to the inside of an unalloyed titanium frame. The outer surface of the spacecraft was made up of shingles of beryllium and René 41 attached to the frame stringers for heat shielding. Titanium accounted for 80 per cent of the structural weight of the capsule.

4.2.6. Gemini

The knowledge and experience gained from the Mercury program resulted in the rapid development of the two-manned Gemini spacecraft (18). The complete spacecraft consisted of two major components, the Adapter Module and the Reentry Module. A thorough trade-off study of various materials resulted in the efficient use of several materials.

Titanium was chosen for the primary structural material of the Reentry Module and a combination of magnesium and aluminum for the expendable Adapter Module. Titanium accounted for 84 per cent of the total structural weight.

The Reentry Module consisted of three sections, the Conical Section, the Reentry and Control System Section and the Rendezvous and Recovery Section.

The Conical Section had an outer surface of René 41 shingles attached to the titanium basic structure. Thermoflex RF insulation blankets were located between the titanium skin and the outer shingle structure. The forebody of the Conical Section was protected by a shield of ablative material. The basic cabin structure was constructed of a fusion welded commercially pure titanium frame and stiffened panels. The side panels and pressure bulkheads of the cabin consisted of two 0.010 in. commercially pure titanium skins (one beaded and one flat), resistance welded together and stiffened by external stiffeners. The external stiffeners were attached by spot welds to the skin. The side panels and the smaller pressure bulkhead were seam welded to the frame. The larger pressure bulkhead was bolted to the frame due to limited accessibility.

The Reentry Control System Section structure consisted of a titanium cylinder with external titanium radial webs attached to stringers. Titanium rings were attached to each end of the structure and beryllium sheet served as an outer skin.

The Rendezvous and Recovery Section was a semi-monocoque design consisting of a titanium inner skin with external stringers and rings covered by an outer skin of beryllium sheet.

The susceptibility of titanium to a pyrophoric reaction in the presence of oxygen was a very important factor which had to be considered when choosing titanium for the primary structural material of the cabins of the Mercury and Gemini spacecraft. A thorough testing program concluded that a pyrophoric reaction would not be a problem at the pressure levels associated with spacecraft cabin structures. No such conclusions could be reached concerning the use of titanium for the high pressure liquid oxygen tanks; therefore, heavier Inconel 718 was chosen.

4.2.7. Atlas

The choice of titanium for pressure bottles in the Atlas missile was one of the main factors that stimulated titanium production after the sharp decline in procurement of titanium mill products which occurred in 1957. Each bottle saved 130 lbs. over a comparable stainless steel bottle (48).

4.2.8. Minuteman

Two early experiments (48) to construct titanium solid-fuel rocket motor cases preceded development of the Minuteman missile. A Ti-6Al-4V alloy motor case resulted in a weight saving of 274 lbs. over a comparable vacuum-melted steel case. Also developed was one constructed of Ti-13V-11Cr-3Al alloy. The Minuteman ICBM, developed in 1960, utilizes a titanium Ti-6Al-4V motor case in its second stage (69).

The final weight is 415 pounds, made from a billet of about 4800 pounds. This application represents the largest demand for titanium in missile applications.

4.2.9. Apollo

Unlike the Mercury and Gemini, the Apollo manned spacecraft has only limited use of titanium (29, 100). Pressure tanks, except the liquid oxygen tanks, are constructed from Ti-6Al-4V and Ti-5Al-2.5Sn alloys, and the escape tower structural tubing is Ti-6Al-4V alloy.

4.2.10. DC-8

In addition to extensive use of titanium in engine pylons and access panels, the DC-8 utilizes rip-stoppers of Ti-6Al-4V throughout the fuselage (48). Rip-stoppers attached to the fuselage frames and around cutouts add significantly to the fail-safe design required of all current jet transports. Titanium serves well in this application due to its good notch toughness.

4.2.11. TFX/F-111

In 1962 the utilization of titanium in airframes was one of the major factors influencing the controversial selection of the General Dynamics design over the Boeing proposal in the multipurpose fighter-bomber (TFX) competition.

Both Boeing and General Dynamics proposed the use of the titanium. The Boeing Design, which called for 17 per cent titanium, included a titanium carry-through structure in the wing. It was felt at the time that Boeing had failed to produce substantiating data on titanium's strength characteristics of structural components of the size

that would be necessary for the wing carry-through structure (54, 104).

The General Dynamics production model (F-111) included a smaller amount of titanium.

4.2.12. SR-71/A-11, YF-12

The SR-71 is the first aircraft which was constructed primarily of titanium (105). Its existence was revealed in 1964, but no publications on its structural details are readily available.

4.2.13. Supersonic Transport

Boeing won the SST competition on December 30, 1966. The proposal is based on using titanium for about 80 per cent of the structural weight. Wing and fuselage consist mostly of skin-stringer construction while honeycomb sandwich panels are used extensively for tail surfaces.

As mentioned in Section 3.4, the discovery of titanium alloys' susceptibility to increased crack propagation in an aqueous environment necessitated re-evaluation of the original decision to use Ti-8AL-1Mo-1V alloy as the primary structural material for the SST.

5. DESIGN CONSIDERATIONS

5.1. General Approach to Design

The preceding sections were concerned with development and structural application of titanium, mostly from the viewpoint of trying to clarify the present technological situation. It has been shown that titanium has reached maturity, that its properties have been well established and, even if problems still exist, that it has taken its place as a major aerospace structural material.

In order to understand the competitive situation of titanium and to assess its potential for the future, it will be necessary to investigate titanium from a different perspective. This is provided by the viewpoint of engineering design. It forms the link between the development of the material, which takes place in the field of material science, and the application of the material, which is the task of structures and production engineering. The designer must look at both material properties and structural application because these two are interdependent from his viewpoint.

In the past, material selection was a rather unsophisticated process. Only few materials were serious contenders. Production facilities and experience weighed heavily against experimenting with new materials and the change from wood to aluminum construction, for instance, took place gradually during two decades. Weight was the dominant criterion. As the strength-to-weight ratio was fairly similar for various materials, an efficient structural design was frequently more important than the choice of the material.

On the other hand, when new materials of higher strength-to-weight ratio are introduced, designers are tempted to use them before the materials are fully evaluated or -- even worse -- before the design criteria are clearly visualized. The introduction of 7075 aluminum is a typical example.

No satisfactory method of evaluating materials for structural application in aircraft is available yet. The subsequent considerations summarize the present situation in this field. They are of a basic nature and are not limited to titanium. However, titanium is the first material which has been developed on a large scale as the need for systematic evaluation became apparent and it may serve as an illustration.

* * *

The evolution of an aerospace structure from conception to operational status involves three significant areas: materials, structures, and design. The interaction between them is disucssed in References 30, 31, and 32, where the interplay of these three disciplines is investigated. Structural guidelines for materials development are indicated in References 1a and 56.

Design may be interpreted in the narrower sense of the word as providing external requirements -- operating loads, temperature and other environmental conditions. It may also be interpreted in the wider sense of engineering design: assuming responsibility for all aspects of the total system. This latter interpretation will be used here. It implies a broad perspective which includes the relationship between materials and structures as well as technological and economic evaluation.

First of all, it is necessary to clarify the basic process which leads to the selection of a particular material and the corresponding type of structure. The following sequence may be established:

a. Definition of overall design function within its economic limitations and reliability requirements;

b. Definition of loading conditions, load spectra, temperature range and other environmental conditions;

c. Tentative selection of material and structure for critical conditions;

d. Comparison with competitive materials and alternate designs;

e. Decision process regarding redesign and final solution.

Items c, d, and e present the fundamental difficulty of an iterative process with a very large number of variables. The objective is to evolve an optimum combination of material and structure where the optimum may be expressed in terms of weight, cost, performance, service life, etc., or any combination of them.

This process of engineering design has often been treated as an art. In the age of computers and systems analysis, it rather evolves into a systematic activity which can be broken down into basic steps. At the present time we are in an intermediate state. Most of our designs in the past were developed by "engineering judgment". Yet we are on the threshold of "design synthesis" -- a new discipline which considers the directed evolution of a design in terms of a defined criterion. Considerable work is being done in this field, but many

difficulties still have to be overcome and a general practical application will not be possible in the near future. References 29a and 84a represent the fast-growing literature on this subject.

Fundamentally, however, any approach to the design problem has to be based on the thinking process which is typical of "engineering judgment". The decisions regarding the selection of a particular material and the corresponding type of structure will have to include a comparison of material characteristics and various types of structures as well as their mutual influence on weight and cost. These influences are considered in the following sections.

5.2. Comparison of Material Characteristics

As stated before, until recently material selection for conventional structures has been a relatively straightforward choice. Now, however, due to the expanding range of operating temperatures and environments and the increasing number of advanced materials, each frequently requiring a different structural concept, material selection becomes a continuous process of stepwise approximation.

Basic parameters for comparison of materials have not yet been established in a generally accepted form. Table II is a list of material rating parameters as suggested in Reference 80. Somewhat different parameters are given in other references. Full agreement will not be reached easily because of a certain amount of interdependence between some of the considerations.

The following parameters are usually considered in the selection of materials for aerospace structures:

(1) Ultimate tensile strength (F_{tu})

(2) Compressive yield strength (F_{cy})

(3) Ultimate shear strength (F_{su})

(4) Fatigue strength

(5) Fracture toughness

(6) Crack propagation

(7) Stiffness

(8) Creep rate

(9) Corrosion resistance

(10) Physical characteristics, particularly density (ρ)

(11) Metallurgical stability

(12) Availability

(13) Fabricability

(14) Maintainability

(15) Costs

(16) Minimum gage

The precedence of these parameters varies with the specific application. Most have to be evaluated for the applicable range of temperature, environmental conditions, time of exposure and stress level.

Comparison of different materials for structural applications usually starts with the following three derived parameters:

(1) Specific tensile strength (F_{tu}/ρ)

(2) Specific compressive yield strength (F_{cy}/ρ)

(3) Specific compressive modulus (E_c/ρ)

In order to provide a ready reference, these derived parameters for typical titanium, aluminum and steel alloys are summarized in Figures 4, 5, and 6. Selected physical properties are listed in Table III. References 21, 26, and 92 contain basic data. Reference 27 is an example of the type of considerations applicable to material selection.

As mentioned before, material selection is a continuing process. Once the preliminary selection of suitable materials has been conducted, based on the preceding derived parameters, re-evaluations have to take place considering other characteristics, fabrication and design problems, temperature, environmental factors and exposure time. Further re-evaluations have to take into account type of structure, weight and costs. It becomes readily apparent that a great amount of detail considerations is required for the process of material selection.

For a comparison between titanium and aluminum, it can be seen from Figures 4 and 5 that a distinction should be made between two important regions of potential application. They are the following:

(1) Application at elevated temperatures above 400°F where the much higher specific strength of titanium may easily outweigh cost considerations for aerospace structures;

(2) Application at temperatures not much higher than room temperature where the specific strength of titanium is moderately higher than for aluminum. In this case, cost considerations play a major role.

5.3. Various Types of Structures

Aerospace structures consist mainly of thin-sheet, thick-sheet or sandwich construction, depending on the structural index which expresses the relative load. Stability considerations are of major importance for parts in compression. Fracture toughness and fatigue are of major concern for parts in tension.

Basically, different materials require different types of structural design for best effectiveness. A few examples will illustrate this point:

(1) For compressive members of sheet-stringer construction in various materials, stability requirements can be met by a different cross-sectional area, a different frame spacing, a different type of sheet-stringer arrangement or by a change to sandwich panels. Each of these solutions has different implications from the viewpoints of design and production;

(2) The feasibility of using extrusions depends on the choice of material;

(3) Assembly techniques vary with the type of material. For example, titanium alloys can be fusion welded, contrary to structural aluminum alloys;

(4) Different design concepts are likely to evolve for different materials. The corresponding expressions for compressive stability will result in different exponents for the modulus of elasticity (59). This indicates that materials with the same specific modulus will have to be evaluated differently for various design applications.

5.4. Weight and Cost

5.4.1. General Considerations

It was indicated at the end of section 5.2 that substitution of titanium in place of aluminum results in a weight saving for corresponding structural components at room temperature. Since the advantages are not as substantial as at higher temperature, this is an outstanding example for the need of balancing weight and cost considerations.

The state of the art regarding weight and cost considerations in aircraft design is shown in Reference 59. This dwells on the basic problem of interaction between material selection and structural application. For this reason, some basic points will be summarized.

5.4.2. Weight and Cost Factors

Changes in weight and cost resulting from any changes in material and structural design are closely interwoven. Since the relationship between weight and cost is of a complex nature and can vary greatly with different assumptions, a basic reference case is usually established. A state of the art design for a given range and payload may serve as such a base case. Other cases with different materials and different structural designs can be compared with this base case.

Overall layout, structural weight, propulsion requirement and fuel load can be determined for this basic aircraft by the preliminary design process. Included must be details of structural concepts because they are necessary for a valid estimate of structural weights. Effects of any change in material or structural design can be analyzed on this basis.

These effects on weight and cost have several aspects. First, a change of material results in decreasing structural weight with increasing strength-to-weight ratio; second, there will usually be some modification of this basic weight relationship due to certain production or design limitations; third, the cost relationship has to include both raw material and fabrication costs; fourth, a change in structural design -- which may or may not be caused by a change in materials -- will effect weight as well as fabrication costs. Most of these effects are best expressed in terms of weight and cost factors. Their meaning will have to be discussed further.

(1) <u>Weight Growth Factor</u>

During the preliminary design of an aircraft, the basic given specifications are frequently payload, range and speed. Keeping these three parameters constant, a reduction in structural weight means smaller propulsion requirements and smaller fuel loads. This results in resizing of the aircraft and a resulting reduction in gross weight which may easily be several times larger than the original structural weight saving. This multiplying effect is expressed by the "weight growth factor" which was pointed out in 1953 in connection with system components (40). It varies considerably with type of design and may involve some non-continuous considerations if changes in powerplants are available in discrete steps only.

Determination of the weight growth factor requires a parametric study including configuration, performance and weight analyses. It is particularly important for trade-off studies during preliminary design.

The underlying assumptions for this type of considerations must be stated very clearly. Instead of keeping payload, range and speed constant, it may be desired to keep payload, gross weight and speed constant. In this case, the reduction in structural weight can be used for additional fuel and corresponding increase in range. A third possibility is to keep range, gross weight and speed constant and vary the payload in accordance with the reduction in structural weight.

(2) Weight Factors

Weight factors can be established in terms of structural design parameters for any structural part. They express the change of weight due to substitution of a different material or different design. The form of this expression depends on the critical design condition for the part which may be strength, stability, fracture toughness, stiffness, etc.

(3) Cost Factors

Cost factors express the change of cost due to substitution of a different material or different design.

Factors indicating the change of cost due to the complexity of manufacturing processes for different materials are of particular importance. A method for applying such factors is shown in Reference 59. Manufacturing operations are broken down to indicate the relative cost of each operation for each material and the distribution of manufacturing operations for each production element. Proper combination of these factors with due consideration for relative weights results in "workability factors" which express the ratio of manufacturing costs

between a new material and a reference material. The procedure necessarily requires a large amount of detail work which can be put in form of a computer program.

5.4.3. Cost Considerations

The designer of aerospace structures is greatly concerned with weight saving. The first question is: How much does it cost? The following considerations refer to aircraft and would have to be modified correspondingly for spacecraft.

For a long time, cost estimates have been based to a large extent on previous experience, usually on data accumulated by each manufacturer and available only to him. Reference 60 represents an attempt to generalize such data. It is based on a systematic survey of cost on military aircraft after World War II and derives equations for cost estimates. Design, Development, Test & Evaluation (DDT&E) costs are separated from Production costs, and each is broken down into many sub-groups. Since these equations are based on past experience with aluminum aircraft, they cannot be applied directly to new materials.

Reference 59 makes use of these data for the cost estimate of various types of aluminum aircraft which are used as base cases.

By means of workability factors as mentioned in section 5.4.2. the costs are estimated for new cases with different materials. Manufacturing labor costs and manufacturing material costs are kept separate and treated in considerable detail. The method starts with cost estimates for detail manufacturing operations and leads up to the total production costs. DDT&E costs are listed independent of production costs.

Some factors influencing production costs deserve further discussion with special reference to titanium.

(1) Raw material costs are high for advanced materials. It is, therefore, imperative to utilize the material as fully as possible. References 35 and 76 consider this aspect. There are many opportunities for the ingenuity of the designer to develop new design concepts in order to avoid excessive machining and to make parts compatible with processing and manufacturing requirements. Increasing use of welding and bonding belongs in this field.

(2) The so-called buy-fly ratio between the material bought and the material flown includes losses due to machining and cutting as well as rejects due to quality control. Reference 59 mentions that values of 2 to 6 for this ratio are representative for aluminum in the aircraft industry. Undoubtedly such values can be reduced considerably. For advanced materials they should be as close to unity as feasible since the price for titanium is about 10 times as much as for aluminum and for beryllium it is about 400 times as much as for aluminum.

(3) Due to the wide variance in mill product prices, special attention must be given to material selection. For example, thinner gages of sheet material are relatively more expensive; commercially pure grades of titanium are cheaper than alloys but have a more limited structural application.

(4) Fabrication costs for titanium show considerable scatter and a wide variety of cost data are quoted in the literature (19, 27, 35, 4, 59). The scatter is a result of a wide range of experience

levels with titanium fabrication among various manufacturers. It takes time to develop experience, and close attention must be paid to details of the technique of fabrication and assembly. Cost data in Reference 19 are based on a survey of the aircraft industry, and a summary of these data is given below:

MANUFACTURING PROCESS	COST FACTOR TITANIUM/ALUMINUM
Forming	1.5-2
Machining	1.5-2
Welding	.8-2
Chemical Milling	3-4
Assembly	1.1
Forging	1.5-2.3
Heat Treating	1.5-5

The data indicate that the costs of titanium fabrication are higher than for aluminum but that they are not necessarily prohibitive.

The preceding considerations are based on production costs. A total cost comparison, however, must take into account three aspects of aircraft costs:

Design, Development, Test and Evaluation (DDT&E)

Production

Operation and Maintenance

It is this third group of operation and maintenance which is particularly favorable for titanium.

Cost of operation for aircraft at constant range, payload and speed depends primarily on gross weight. This influence is shown in Reference 12. Solely considering the saving in fuel cost due to reduced weight may result in several hundred dollars per pound of weight reduction during the lifetime of a supersonic transport.

Cost of maintenance depends on many factors. A very important aspect is shown in Reference 4: Aluminum aircraft, particularly in the Navy, require much maintenance for corrosion control. Titanium aircraft are not susceptible to corrosion and the decreased number of manhours required for maintenance results in greater operational availability, possibly even in a smaller number of aircraft required to perform a given mission. The overall effect of this freedom from corrosion combined with a reduced gross weight may be great enough to balance the higher initial investment cost for a titanium aircraft by lower operation and maintenance costs.

There is another aspect to this "system cost", based on trade-off studies between titanium and aluminum. It is summarized briefly in Reference 35 and discussed in detail in Reference 4. Assuming constant range and payload, aluminum parts are sequentially replaced by titanium, investigating weight and cost at each step. Those parts where the advantages of titanium substitution seem most obvious are replaced first, and system costs are shown to reach a minimum when about 30 to 60 percent of the aluminum is replaced by titanium.

A further consideration which cannot easily be assessed from the viewpoint of economics concerns damage tolerance and repairability. Damage may be due to fatigue cracking, accident or military action. Titanium has higher tear resistance than high-strength aluminum and can, therefore, contain damage better. Repairability depends mostly on detail design considerations.

5.4.4. Value of Weight Saving

The preceding section 5.4.3 was concerned with the question: "How much does weight saving cost?" . The present section will consider the corresponding question: "How much is weight saving worth?".

An appraisal of the value of weight saving in dollars per pound provides an important guideline for making design decisions. A rule of thumb value of about 40 or 50 dollars per pound had been used widely in the aircraft industry for many years (40). Yet much higher values can be derived and values as high as 10,000 dollars per pound are quoted for some upper stages of space vehicles (100). A correct value can be determined for each case when the conditions are clearly defined.

The discussion about the weight growth factor in section 5.4.2 shows the importance of defining a reference criterion, e. g. constant range and payload, and of analyzing the effects of any changes in materials or structures. Some of these effects increase and others decrease the overall cost of the aircraft system. In many cases the cost-increasing effects are easily visible, and the cost-decreasing effects are somewhat hidden. It is seen from the considerations in

section 5.4.3 how closely interwoven these two effects are. Cost-decreasing effects actually determine the value of weight saving.

It must be realized that the value of weight saving varies during the design process. In the early stages of preliminary design, weight changes result in resizing of the aircraft and the weight growth factor has its full importance. After the aircraft configuration has been frozen, weight saving assumes a different value which may easily be influenced by secondary causes.

Material selection and structural concepts are mostly determined during the early stages of preliminary design when resizing of the aircraft configuration is possible. The corresponding weight growth factor as well as cost of operation and maintenance have a major influence on the value of weight saving. The determination of this value, as shown in section 5.4.3, involves complex design considerations. Yet it is of fundamental importance to determine it as clearly as possible.

Reference 27 shows a convenient method of plotting cost versus weight of structural components in different materials and comparing their efficiency by means of the sloping line which indicates the value of weight saving in dollars per pound.

6. RELATIONSHIP BETWEEN MATERIAL AND STRUCTURAL APPLICATION

Tracing the development of titanium through the last two decades, it becomes obvious how close the relationship is between material and structural application. Much of this is felt intuitively. To clarify it and to prepare the ground for a basic approach to the problem, a distinction should be made between two different aspects of this relationship:

(1) material <u>development</u> and structural application;

(2) material <u>selection</u> and structural application.

The preceding sections will now be summarized from these two viewpoints.

6.1. Material Development and Structural Application

The relationship between material development and structural application is of particular concern to the overall planning for the development of new materials. In this field, much can be learned from the experience with titanium:

(1) The review of the first decade of titanium production indicated the difficulties in developing an alloy of uniform quality and experimenting with fabrication methods. Many different alloys were explored and applied to airframes by experimental techniques. A good number of companies were involved and it seems that coordination between various developments was somewhat lacking. In spite of much valuable work which was done, from the viewpoint of interrelation between material development and structural application the results were less than expected.

(2) A decisive step toward improving this interrelation was taken with the Titanium Alloy Sheet Rolling Program. From its very beginning, the need for establishing the closest possible relationship between material development and structural application was clearly recognized. Titanium producers and aerospace manufacturers cooperated fully in a well coordinated effort. The resulting alloys and fabrication techniques laid the foundation for the expansion of titanium application in the aerospace industry.

(3) After this foundation was laid, it became possible to apply titanium on a somewhat larger scale as it was done on the Lockheed SR-71, the McDonnell Mercury and Gemini capsules, and others. Experience was gained and fabrication techniques were further improved.

(4) A new order of magnitude became applicable with the design of the supersonic transport, a project of far-reaching economic importance based completely on the structural application of titanium alloys. This required assurance that the material had been tested under all environmental conditions which might possibly occur.

(5) Early anticipation of difficulties and provision for their systematic solution is essential in any development process. In the case of titanium, considerable problems in production and fabrication were anticipated from the beginning and were solved laboriously by wide-spread and time-consuming efforts.

(6) It is also quite important to realize the possibility of unexpected problems. They appeared for titanium after one-and-a-half decades of development due to stress corrosion cracking and crack propagation under certain environmental conditions, as outlined in section 3.4.

(7) Thorough testing requires a great number of combinations of temperature, exposure time, stress, sequence of cycling and environmental atmosphere. It may have to be limited due to time or budget restrictions. Since the causes for some of the failure phenomena are not yet fully understood, the determination of the most critical test conditions is somewhat elusive. The combination of these circumstances is an ever-present danger until a new material has come of age.

6.2. Material Selection and Structural Application

The relationship between material selection and structural application is of particular concern from the viewpoint of engineering design. It is a field in which not much systematic work has been done yet. Its importance, however, is increasingly recognized. In this respect, titanium is in no position to serve as a source of special experience, but it rather serves as a stimulant which attracts attention to the subject.

It was seen in section 5.4 that titanium may possibly be competitive with aluminum at room temperature under certain conditions. An answer to this question requires a thorough systems analysis which has to be based on the interaction between material and structure, with much emphasis on cost effectiveness of the total system. An approach to this problem with presently available methods was discussed in section 5.4.

This approach is based on an analytical process. It starts with the properties of a given material and finds the corresponding weights and costs by meticulous consideration of detail influences. It represents our present state of the art.

The typical design problem, however, is more than an analytical problem. Instead of analyzing for a given combination of material and structure, it consists of finding an optimum combination of material and structure which meets various design conditions.

This involves considerations in the fields of materials, structures and systems engineering as well as optimization methods from the field of operations analysis. It represents a complex problem and a solution is not yet in sight. But being aware of this problem is helpful in directing attention to some basic points.

One of these basic points is that material selection, from the viewpoint of engineering design, requires comparison of a great many critical material parameters. The complexities of the problem are indicated in section 5.2. Yet it will not be possible to apply materials efficiently at complex environments and loads until a basic method of evaluating materials for structural application is established.

Each material generally requires a different type of structure. This influences weight and cost. These relations will have to be put in a form as clear and simple as possible.

Regarding cost effectiveness, engineers have been cost-conscious for a long time. Their concern, however, has been mostly in minimizing production costs of structural components. Little has been done to determine the influence of materials and overall design on cost of operation and maintenance.

It is seen from these considerations that an essential task consists of establishing those fundamental parameters which influence material selection and structural application. This can lead toward a methodology which will be useful for an analytical approach and which, at the same time, will form the foundation for future work toward the basic design problem of finding an optimum solution.

7. CONCLUSIONS

Titanium in aerospace structures provides a valuable case study for development and application of a new material. It is particularly instructive because titanium is the first material developed on a large scale specifically for the complex conditions of high-performance aircraft. Other advanced materials may have to go through a similar development process in the near future, even if it will be on a smaller scale.

From the viewpoint of trying to learn from past experience for future developments, the following points are considered to be significant:

(1) An overall study of titanium development and structural application provides an insight into the awesome complexities and difficulties of such a program as well as the marked effect of government subsidies. It is an outstanding example for the great responsibilities which have to be assumed in connection with the development of a new material.

(2) At the beginning of a program of material development, a clear assessment of the potential of the new material is necessary. In the case of titanium, high specific strength at elevated temperatures, high corrosive resistance and good fatigue characteristics were distinct assets from the very start. Its ability to alloy easily with other elements guaranteed a wide range of mechanical properties. The raw material was amply available. The initial market was militarily inspired and government-financed.

(3) Technological assessment has to be coupled with economic assessment. This includes research and development cost as well as anticipated future production cost utilizing the new material. The latter depends on quantity of production, and its prediction causes considerable difficulty.

(4) Decisions have to be made to concentrate the development efforts on a limited number of the available alloys. There is a danger of over-diversion which can be detrimental to thorough testing programs.

(5) Test programs have to include exposure time at various temperatures and other environmental conditions. Such tests extend over long periods. As in so many of our engineering developments, time is usually at a premium, and it is frequently not possible to evaluate one step completely before the next step is taken. Whenever this is done, proper provision must be made for the risks which are involved.

(6) When engineering requirements can be satisfied by various materials and designs, decisions have to be based on cost effectiveness. An accurate cost breakdown must include the costs of the overall system, including operation and maintenance. Many of the analytical methods for cost analysis have to be developed in the engineering department because they are based on the interaction between materials and structures. Engineers should become increasingly aware of this important aspect.

(7) Weight considerations are a part of cost effectiveness because weight can be expressed in terms of cost. Established methods for cost estimation are complex and do not lend themselves easily to a ready comparison of various materials and structural concepts.

(8) A final remark may be made with respect to a changing situation. When titanium was developed during the past two decades, its structural application was assured due to its outstanding specific strength at temperatures occurring during the present supersonic flight regime. Detail problems of production, fabrication and material characteristics overshadowed other considerations, e.g. cost comparisons.

The development of future materials is likely to take place under different circumstances. As trade-off studies between weight and cost will be essential, advanced materials and the corresponding structural design will have to be closely scrutinized for the most effective combination.

This will require new methods, based on systematic work in many fields. Basic parameters for material evaluation have to be established. Structural concepts have to be translated into mathematical models. Cost analysis has to be put in the form of an engineering tool. Optimization methods have to be applied.

Above all, a close relationship has to be established between the fields of materials, structures, operations analysis and systems engineering. This is a fundamental challenge. Interaction between materials and structures will play a dominant role and may be considered the focal point in these considerations.

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TABLE I

STRUCTURAL APPLICATION OF TITANIUM
(Percentage of Structural Weight)

1948-1952			1953-1957			1958-1963			1963-Present		
Vehicle	%	*	Vehicle	%	*	Vehicle	%	*	Vehicle	%	*
F3H	0.3	M	F-101	2.9	M	Mercury	80.0	N	SST	80.0	B
AJ	1.0	N	A3J	7.0	N	Gemini	84.0	N	SST**	68.0	L
F86	1.0	N	F4B	7.5	M	727	3.0	B	SST**	74.0	N
B-52A	0.8	B	F-100	7.0	N	TFX**	17.0	B	F4K	9.4	M
			B-52G	2.0	B	SR-71	75.0	L			
			XB-70	9.0	N						
			X-15	17.5	N						

* Company
B -- Boeing
L -- Lockheed
M -- McDonnell
N -- North American

**Proposals Only

TABLE II

MATERIAL RATING PARAMETERS FOR SUPERSONIC TRANSPORTS (80)

(a) Discriminating Parameters

1. Strength	The average of the short-time ultimate tensile strength and compression yield strength at room temperature and 650°F divided by the material density.
2. As-welded strength	Ratio of the ultimate as-welded tensile strength to the ultimate design tensile strength of the parent metal.
3. Fatigue	Fatigue strength (10^5 cycles of axial tension, R = 0, and a stress concentration factor of $K_t = 2.5$) at room temperature divided by density.
4. Stiffness	The average Young's Modulus in tension between 70°F and 650°F divided by the material density.
5. Thermal stress	Average coefficient of thermal expansion between 70°F and 650°F times Young's Modulus at 650°F divided by compression yield strength at 650°F.
6. Toughness	Minimum values of notched over unnotched tensile strength ratio in the temperature range -110°F to 650°F. The choice of ASTM machined edge notched specimen or 8-inch fatigue cracked specimen should be based on the amount of test data available. Only one type of specimen (either notched or cracked) should be used in the rating procedure. If the amount of data for notched and cracked specimen is approximately the same, the cracked specimen is recommended.
7. Stability	Ratio of the notch-strength after exposure to the notch-strength before exposure.
8. Cost	The product of the cost (dollars per pound) of 10,000 pounds of sheet material (0.050 inch x 36 inch x 96 inch) and 10^5 divided by the strength parameter (refer to strength).

(b) Nondiscriminating Parameters

1. Availability	Relative supply of raw material and equipment for production by 1965.
2. Producibility	Producers' capability to offer raw material in form of sheet, foil, and plate.
3. Formability	Uniform elongation of three per cent in 2-inch gage length.

(c) Go-No-Go Parameters*

1. Corrosion	Resistance to general corrosion and stress corrosion for supersonic transport environment and life.
2. Weldability	Can be fusion welded with freedom from voids and cracks.
3. Brazability	Capability as a brazed-sandwich panel to retain the properties of the basic material.

*The go-no-go parameters represent characteristics of a material to which quantitative values can be assigned, but which must meet a certain fixed minimum value.

TABLE III

SELECTED PHYSICAL PROPERTIES OF SELECTED TITANIUM, ALUMINUM AND STEEL ALLOY SHEET (96)

PROPERTY / ALLOY	DENSITY (lbs/in^3)	THERMAL EXPANSION ($in/in/^{\circ}F$) ROOM TEMPERATURE TO $200^{\circ}F$	THERMAL CONDUCTIVITY ($BTU/ft^2\text{-}hr\text{-}^{\circ}F/ft$) $200^{\circ}F$	$E\alpha$ ROOM TEMPERATURE
Ti-8Al-1Mo-1V (DUPLEX ANNEALED)	0.158	5×10^{-6}	4	87.5
Ti-6AL-4V (SOLUTION TREATED AND AGED)	0.16	5.3×10^{-6}	4.3	85
2024-T86 ALUMINUM	0.10	12.9×10^{-6}	80	135
AM 355 STEEL	0.282	6.9×10^{-6}	9	200

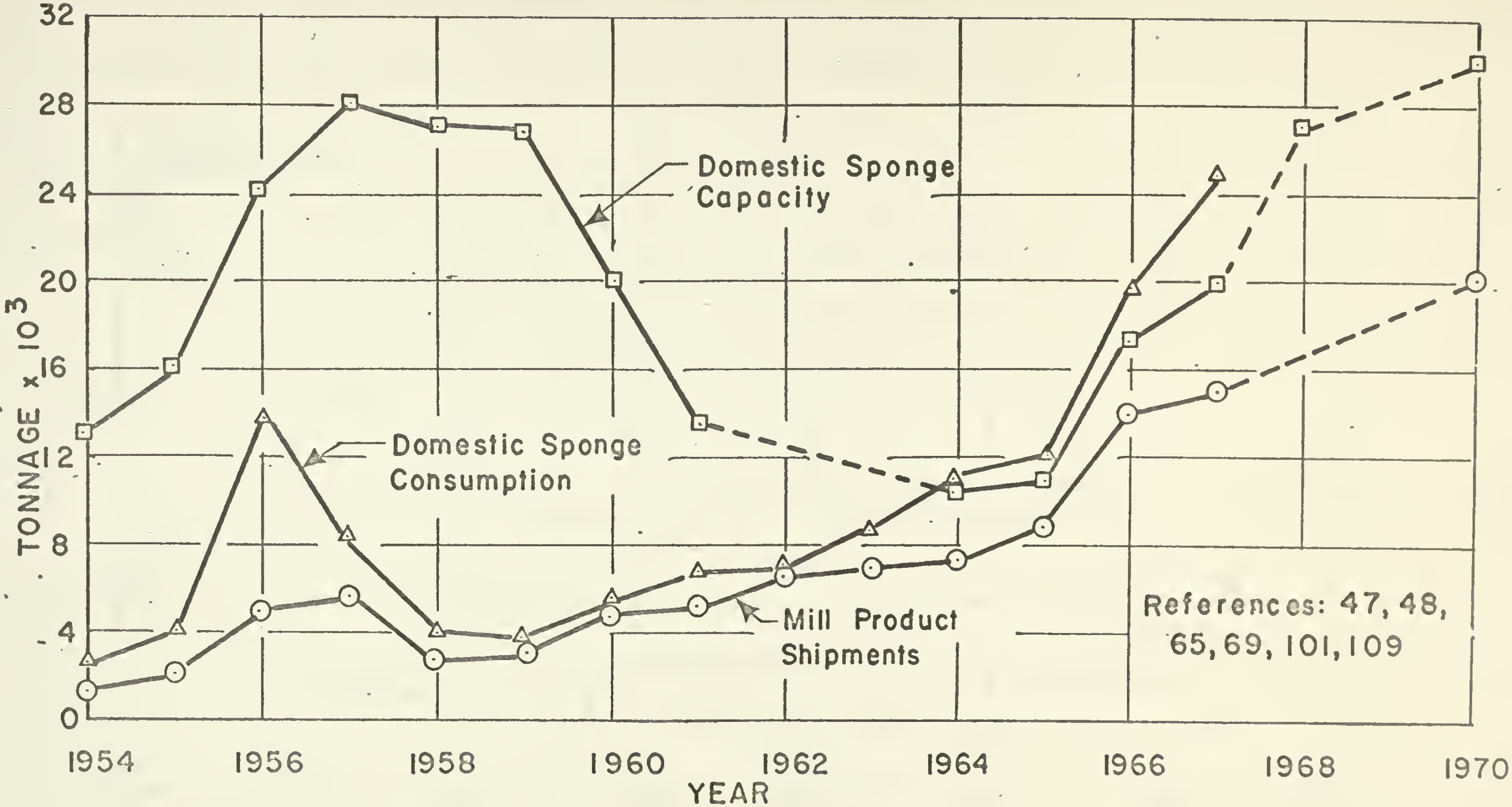

FIGURE I. TITANIUM PRODUCTION HISTORY

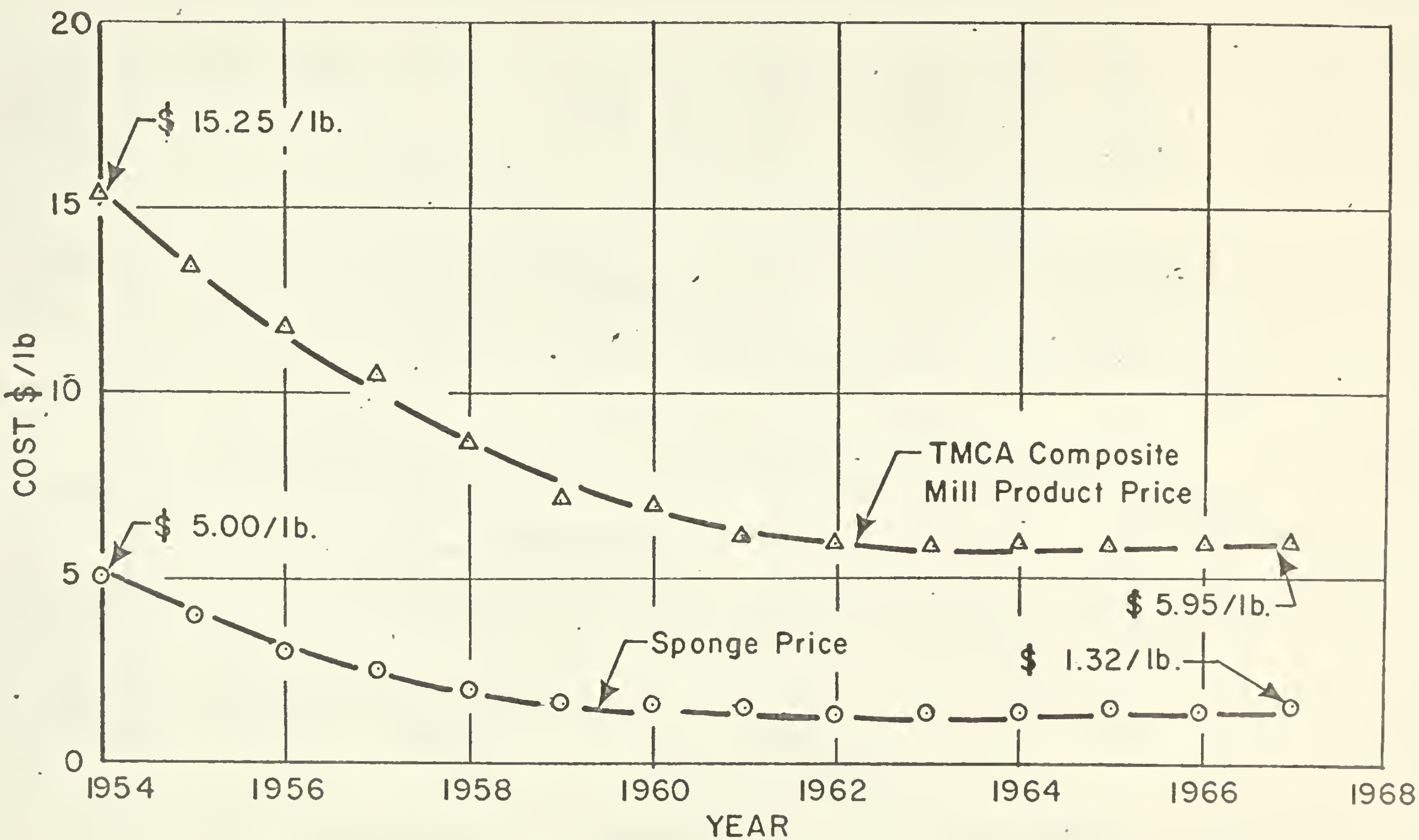

FIGURE 2 TITANIUM SPONGE AND MILL PRODUCT COST

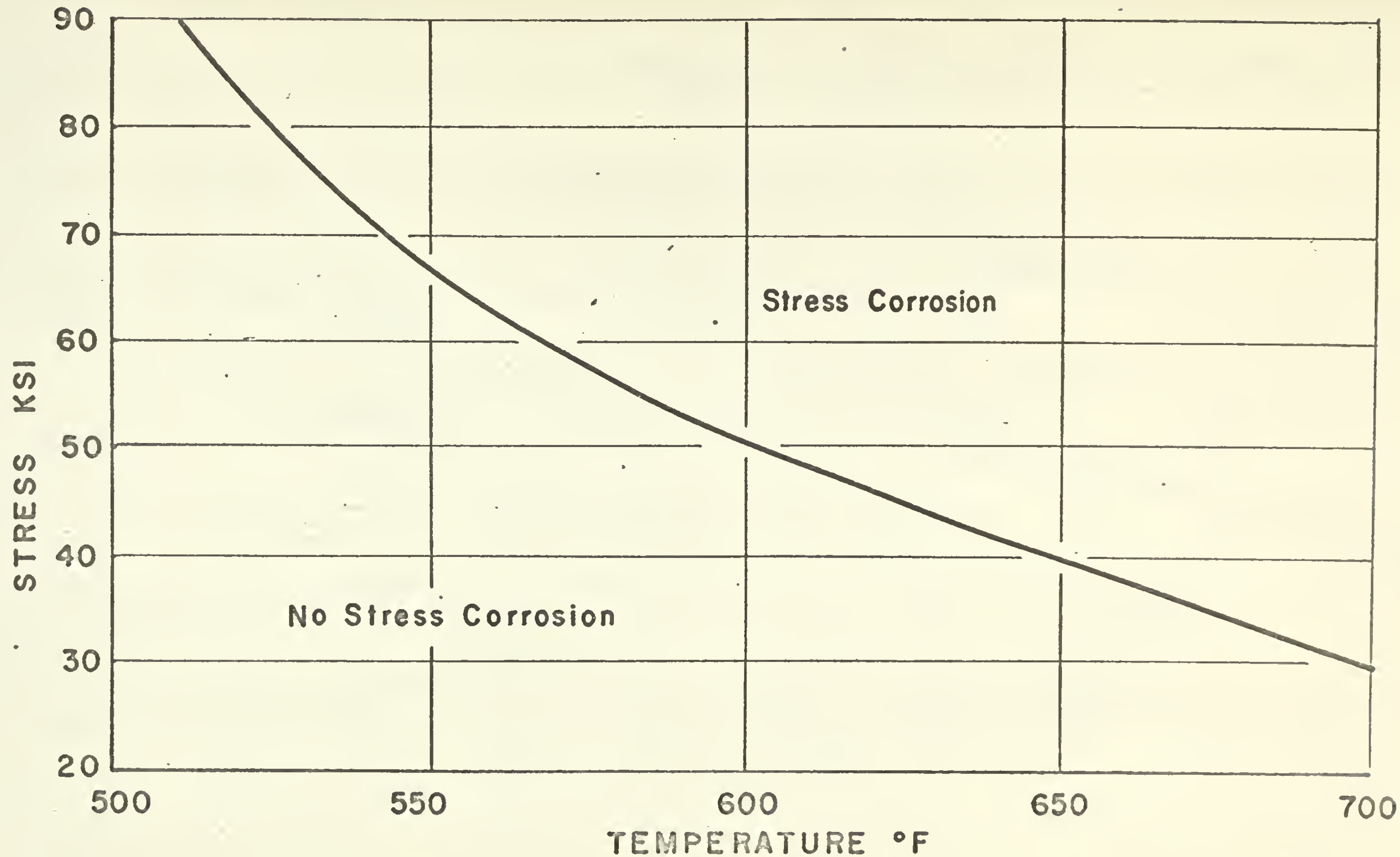

FIGURE 3 THRESHOLD FOR HOT-SALT STRESS CORROSION OF TI-6AL-4V SHEET (1,000 HR. EXPOSURE)

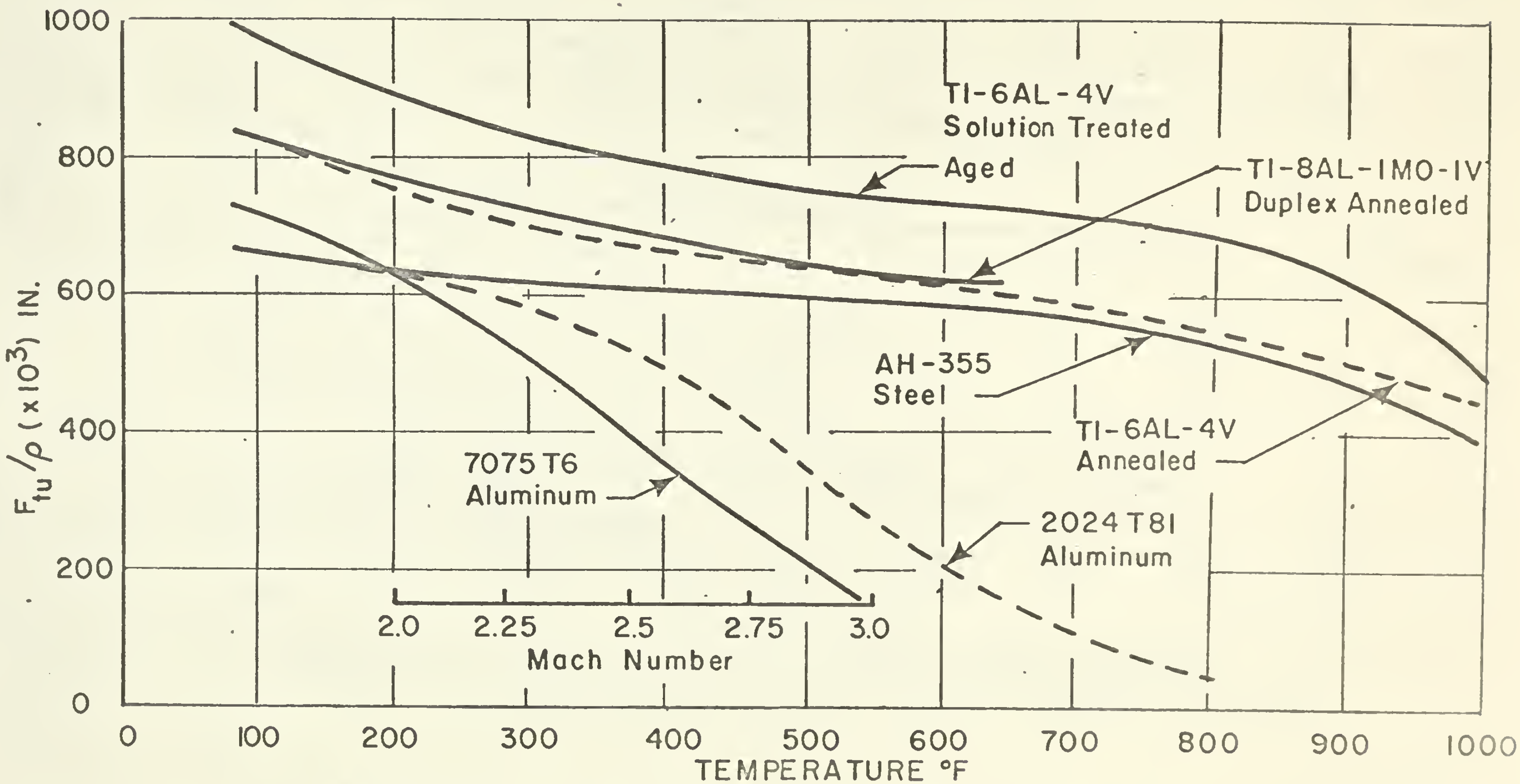

FIGURE 4 SPECIFIC TENSILE STRENGTH VS TEMPERATURE (SHORT TIME EXPOSURE)

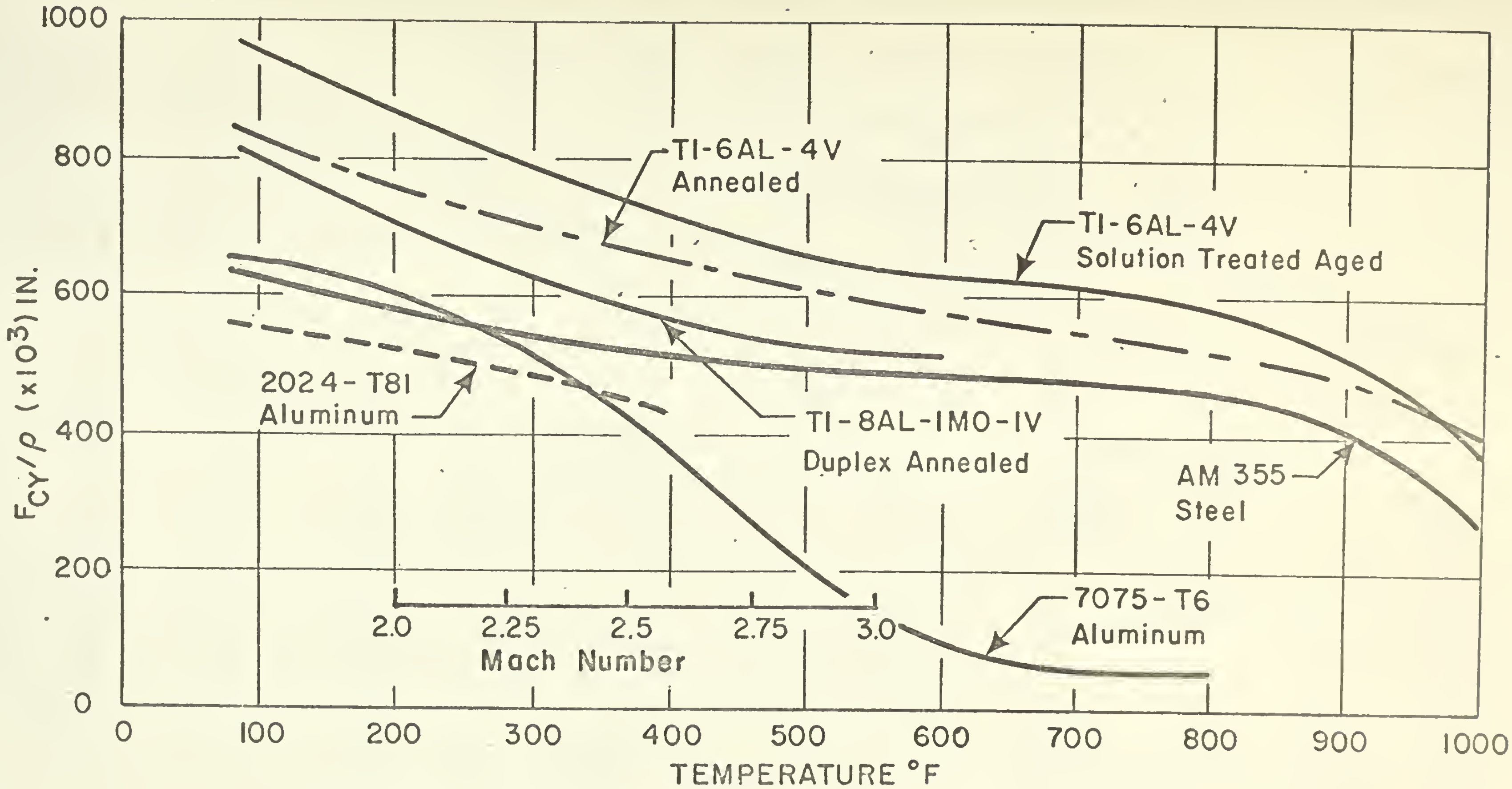

FIGURE 5 SPECIFIC COMPRESSIVE YIELD STRESS VS TEMPERATURE (SHORT TIME EXPOSURE)

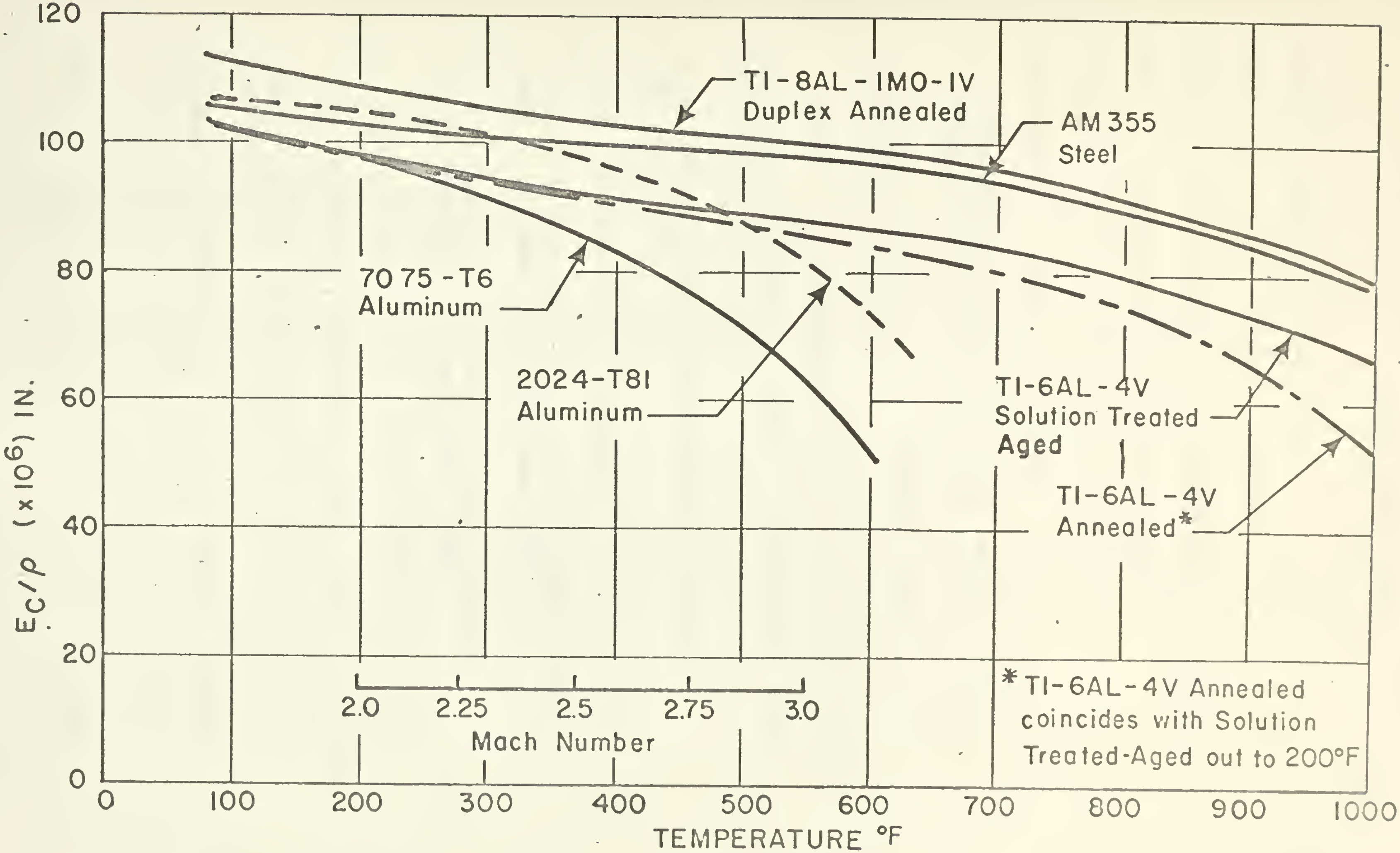

FIGURE 6 SPECIFIC COMPRESSIVE MODULUS VS TEMPERATURE (SHORT TIME EXPOSURE)

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13. ABSTRACT

Material development and structural application of titanium are reviewed for the purpose of making the accumulated experience available for the development of future advanced materials. Two types of interaction are considered: materials development and structural application as well as materials selection and structural application. The process of selecting a material for structural application is investigated from the viewpoint of engineering design. It is shown that titanium provides a valuable case study because it is the first material developed on a large scale for the complex conditions of high-performance aircraft.

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